



Statistical Modeling of Yield and Variance Instability in Conventional and Organic Cropping Systems

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ABSTRACT

Temporal variation in crop yields has considerable impact at farm, regional, and national levels. To gain a better understanding of the factors contributing to this variation, we quantified the cumulative effects of management practices and soil covariates on total yield (TY), temporal yield variance (TYV) and coefficient of variation (CV) of 2-yr (2 Yr) {corn [*Zea mays* L.]-soybean [*Glycine max* (L.) Merr.]} and 4-yr (4 Yr) [corn-soybean-spring wheat (*Triticum aestivum* L.)-alfalfa (*Medicago sativa* L.)] crop rotations in conventional (CNV) and organic (ORG) cropping systems. Soil covariates differed individually or as a group in their impact on TY, TYV, and CV. Spatial variation, quantified by soil covariates, did not fully explain variation in TY or TYV; whereas, TYV explained up to 86% of variation in TY, both of which were less variable in ORG than in CNV. Multivariate relationships among TYV, CV, management factors, and covariates indicated that TYs of 4-Yr crop rotations were likely to be more stable than TYs of 2-Yr rotations. The largest and most stable yields obtained under both cropping systems are characterized by a combination of optimum TYV and minimum CV values. We developed a classification scheme of cropping systems, crop rotation phases, and management practices based on the three-way relationship between TY, TYV, and CV, and deviations from their respective means. In addition to its utility in selecting the largest and most stable yield, the scheme can be used to measure stability in crop production and strategically deploy appropriate management practices for a given cropping system or crop rotation.

THE DIVERSITY AND INTENSITY of cropping systems in the Corn Belt have been changing over time in response to several interacting biophysical and social factors (Posner et al., 2008). During the second half of the 20th century, cropping systems in large parts of the Corn Belt became more specialized at field, farm, and landscape levels, where reduction in number of crops and variability within fields led to the development of monocultures that potentially increase environmental risks because they reduce biodiversity, ecosystem functions, and ecological resilience (Rozenzweig and Tubiello, 2007). The long-standing debate over the trajectory of extensive cropping systems based on the corn-soybean rotation in the Corn Belt deserves a new look because it focuses on a single ecosystem service (i.e., production), overconsumes environmental resources, and releases chemicals to the environment (Turinek et al., 2009).

The sustainability of cropping systems is most effectively evaluated by long-term experiments that simulate management practices and conditions encountered in farmers' fields (Singh and Pala, 2004). Moreover, long-term experiments are necessary if the sustainability of a production system is to be determined, such that long-term yield trends, dynamics of the availability and balance of nutrients and capacity of the soil to maintain productivity over time can be measured (Stanger and Lauer, 2008). Long-term experiments, which provide a measure of sustainability, can be

used to detect problems that may affect productivity (Berzsenyi et al., 2000). Due to their complex nature, cropping systems cannot be fully studied using reductionist (e.g., factorial) experiments (Drinkwater, 2002); whereas, a systems approach, where treatments represent intact management strategies, is more powerful in elucidating how functions of a cropping system (e.g., yield) are determined by the interrelationships among treatments and biophysical processes (Drinkwater, 2002; Brandt et al., 2010).

An ideal study site for cropping systems experiment is a land area representative of a large ecogeographical region, in which the plot size and soil variability have been optimized for a specific crop, crop rotation, or treatment (Legendre et al., 2004). Finding such an experimental field is a challenge in large parts of the upper Midwestern United States where research on field stations was originally developed for and continues to be devoted to small, randomized plot experiments (Cambardella et al., 1994; Porter et al., 2003). A combination of reductionist and holistic systems approaches in the design and analysis of long-term experiments is essential for understanding the complex interactions of plants, soils, climate, and management (Fagroud and van Meirvenne, 2002). This approach is also critical in estimating the covariance or correlation structure of experimental errors over time (Singh and Jones, 2002) if clear insights into the effects of crop rotation and the management or input factors associated with them are to be obtained. Spatial (between-plots) and temporal (within-plot) variation are the major components of

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Abbreviations: 2Yr, two-year rotation; 4Yr, four-year rotation; A, alfalfa; BD, bulk density; C, corn; C/N, carbon to nitrogen ratio; CNV, conventional cropping system; CT, conventional tillage; ECaH, horizontal apparent electrical conductivity (dS m^{-1}); ECaV, vertical apparent electrical conductivity (dS m^{-1}); F, fertility; IC, inorganic carbon; MBC, microbial biomass carbon; NF, nonfertilized; ORG, organic cropping system; pH, soil reaction; R, rotation; S, soybean; SC, soluble carbon; ST, strip-tillage; T, tillage; TY, total rotation yield; TYV, temporal yield variance; W, wheat; YF, fertilized.

variance of crop response (e.g., yield) in cropping systems experiments. The spatial component indicates the variation due to the interaction of crop management factors and other covariates which change across a landscape such as soil properties; whereas, the temporal component indicates the magnitude of changes occurring over time from the interaction of management and landscape effects (Blackmore et al., 2003; Singh and Pala, 2004).

A major challenge to production research is to understand how management decisions affect crop yields, and then be able to use this understanding to predict and/or control crop yield variability (Bachelor et al., 2002). Cropping systems research is critical to gaining this understanding as it helps distinguish between the effects of management and those of spatiotemporal variation. Cropping systems research in the upper Midwest is underway to reverse the declining crop diversity (Varvel, 2000; Posner et al., 2008) and verify competitiveness of environmentally-sound (Porter et al., 2003; Posner et al., 2008) and economically-viable (Archer et al., 2007) alternative cropping systems. Porter et al. (2003) described how rotation length and management strategies influenced productivity after, but not during, the initial four establishment years of a cropping systems experiment; whereas, Archer et al. (2007) concluded that transitioning to low-input organic production systems can be economically viable during the initial years of their establishment. Notwithstanding the temporal variability of crop response, several researchers (e.g., Porter et al., 2003; Posner et al., 2008; Riedell et al., 2009) suggested that more diverse crop rotations and alternative management can be effective at reducing long-term yield variability. However, when spatial patterns are present in experimental sites, appropriate systematic designs and powerful statistical analyses procedures are needed to obtain more precise estimates of treatment effects (Blackmore et al., 2003; Brandt et al., 2010). The objectives of this study were to (i) characterize the experimental site and estimate its spatial variation, (ii) quantify and model the cumulative effects of alternative management factors and spatial variation (quantified by soil covariates) on total rotation yield and its temporal variance and coefficient of variation under conventional and organic cropping systems in the upper Midwest, and (iii) develop a classification scheme to help identify management strategies that can capitalize on temporal yield variation under field conditions.

MATERIALS AND METHODS

Site and Soil Description

The Swan Lake Research Farm of the North Central Soil Conservation Research Laboratory is located in Stevens County in West Central Minnesota (45°41' N, 95°48' 370 masl). The region is glacial-till prairie and is dominated by Udolls, Udalfs, Aqualfs and Aquolls. Five soil series identified within the Swan Lake Research Farm experimental site (USDA-SCS, 1971), were: Barnes loam (fine-loamy, mixed, superactive, frigid Calcic Hapludolls), Flom silty clay loam (fine-loamy, mixed, superactive, frigid Typic Endoaquolls), Hamerly clay loam (fine-loamy, mixed, superactive, frigid Aeric Calciaquolls), Parnell silty clay loam (fine, semectitic, frigid Vertic Argiaquolls), and Vallery silty clay loam (fine-loamy, mixed, superactive, frigid Typic Calciaquolls). The site was cropped uniformly with soybean for a year to minimize residual effects of previous treatments.

Experimental Design and Layout

A long-term cropping systems field experiment was established in 2002 on a land area of about 3.3 ha as a split-plot randomized complete block design with four replications (Archer et al., 2007). Two cropping systems (SYS) that is, CNV and ORG were randomly assigned to each of two blocks per replicate within which two levels each of crop rotation (R), tillage (T), and fertilizer (F) management factors were randomly applied to subplots. One of two subfactor levels for each main management factor were randomly assigned to each subplot as follows: for R, a 2-Yr corn-soybean rotation; or a 4-Yr corn-soybean-spring bread wheat-alfalfa/alfalfa rotation; for T, conventional, CT, or strip-tillage, ST; and for F, no fertilizer, NF, or with fertilizer, YF. Conventional and strip tillage were conducted in the fall using a moldboard and chisel plow, respectively. Weeds were managed with appropriate chemical application in CNV and by rotary hoeing, harrowing, or field cultivation in ORG as dictated by the crop and weed emergence. Fertilizer rates were determined for each crop on the basis of soil analysis and regional N recommendations, with inorganic N for CNV and animal manure for ORG. The experimental design also included all phases (i.e., entry points) in each crop rotation to be grown such that each year the two phases of the 2-Yr crop rotation (corn-soybean (CSCS) and soybean-corn (SCSC)) and all four phases of the 4-Yr crop rotation (alfalfa-corn-soybean-wheat (ACSW), corn-soybean-wheat-alfalfa (CSWA), soybean-wheat-alfalfa-corn (SWAC), and wheat-alfalfa-corn-soybean (WACS) were represented. All phases of each crop rotation and management factors were exposed to the same environmental conditions during the course of the experiment, thus eliminating the need to quantify their interaction with the environment in the current statistical analyses. This design resulted in 24 RTF-rotation phase combinations for each of two cropping systems randomly distributed over four replicates with a total of 192 plots. A cropping system was defined as the producers' map of their approach to crop production.

Soil and Yield Sampling

To quantify the spatial variation and characterize the experimental site, each of the 192 experimental plots (6 by 12 m) was sampled in depth increments of 0 to 15 cm and 15 to 30 cm in the fall of 2002 and spring of 2003 to establish baseline soil conditions. Two soil cores (7.6 cm in diameter) were taken near the center of each plot. One core was used for soil chemical analysis and the other core was used to analyze physical attributes (Table 1). In addition, three 1.9 cm diam. cores were taken at the 0- to 15-cm depth increment and composited for each plot and used for microbial biomass carbon (MBC) and soluble carbon (SC) analyses. Samples were analyzed for several physical, chemical, and biological attributes and variables (Table 1). Horizontal (ECa-H) and vertical (ECa-V) apparent electromagnetic conductivities (dS m^{-1}) were measured on two georeferenced subplots per plot using a Geonics EM38 (Sudduth et al., 2003). Particle size analysis was determined on soil from the surface 0 to 15 and 15 to 30 cm. Soil pH_(H2O) was measured using 2:1 water/soil ratio (Thomas, 1996). Soluble carbon was extracted with 0.5 M potassium sulfate (K_2SO_4) from fresh soil immediately after sampling. Microchemical oxygen demand tubes (20–900 mg L^{-1} range) (Fisher Scientific, Pittsburgh, PA) were used for determining the concentration of SC. Microbial biomass

Table 1. Descriptive statistics, tests of significance, percent structural variance, and spatial class for soil covariates in a cropping systems field experiment.

Soil attribute/variable	Depth cm	Mean†	CV	Skew ratio‡	Kurtosis ratio‡	p(S-W)¶	GIS Model	R ²	Structural variance	Spatial class §
Sand, %	0–15	36.30	10.8	1.41	–2.21	0.003	Linear	0.23	0.75	M
	15–30	35.41	12.8	0.54	–2.00	0.034	Linear	0.25	0.86	S
Silt, %	0–15	36.22	10.5	1.21	–0.41	0.210	Spherical	0.43	0.89	S
	15–30	35.82	11.1	–0.95	–1.57	0.070	Spherical	0.46	0.89	S
Clay, %	0–15	26.58	12.1	–8.11	12.59	0.001	Spherical	0.48	0.94	S
	15–30	27.04	16.1	–8.01	9.35	0.001	Spherical	0.52	0.93	S
Bulk density	0–15	1.17	4.0	3.6	2.3	0.001	Exponential	0.03	0.82	S
	15–30	1.21	6.2	3.2	2.5	0.001	Exponential	0.12	0.75	M
pH	0–15	7.62b	3.9	–9.45	6.69	0.001	Gaussian	0.14	0.75	M
	15–30	7.73a	3.5	–6.59	2.54	0.001	Gaussian	0.20	0.77	S
Electrical conductivity, dS m ^{–1}										
Horizontal, ECaH#		29.6a	18.9	1.77	1.50	0.001	Spherical	0.96	0.55	M
Vertical, ECaV		33.4a	18.1	2.50	1.66	0.001	Spherical	0.98	0.61	M
Carbon, C										
Inorganic, IC, %	0–15	0.23b	42.0	6.35	1.19	0.001	Gaussian	0.89	0.78	S
	15–30	0.43a	35.7	5.86	0.35	0.001	Gaussian	0.78	0.75	M
Soluble, SC, [mg kg ^{–1} (×1000)]		0.08	33.2	1.71	0.36	0.370	Exponential	0.91	0.88	S
Microbial, MBC, [mg kg ^{–1} (×1000)]		0.97	19.2	0.48	–1.35	0.247	Spherical	0.69	0.92	S
C/N	0–15	12.97b	9.1	6.18	1.15	0.001	Spherical	0.00	0.92	S
	15–30	14.68a	10.2	7.17	2.3	0.001	Spherical	0.08	0.87	S

† Values followed by the same letter are not different (Tukey HSD, $p < 0.05$) among depths for a given soil attribute/variable.

‡ Bold face values for Skewness and Kurtosis ratios are significant, $p < 0.05$.

¶ Bold face values for probability of a significant Shapiro–Wilk test [P(S-W)] are normally distributed.

§ Spatial class: S, strong spatial dependence; M, moderate spatial dependence.

ECaH, horizontal apparent electrical conductivity; ECaV, vertical apparent electrical conductivity; SC, soluble carbon; MBC, microbial biomass carbon.

C was estimated by subtracting the SC in nonfumigated soil from the SC in a chloroform-fumigated soil and multiplying the difference by 2.64 (Vance et al., 1987). Soil concentration of total N and total C were measured using a LECO CN-2000 (LECO Corp., St. Joseph, MI). Inorganic carbon (IC) was determined using an automated volumetric analysis system (Wagner et al., 1998). Grain yield in each of the first four establishment years (2002–2005) of this ongoing experiment was measured from a central 1.5 by 10 m mechanically-harvested strip per plot, and from two georeferenced 1-m² hand-harvested subsamples per plot of corn, soybean, and wheat and adjusted to a moisture content of 15.5, 13.0, and 13.5%, respectively. Total dry matter yield of alfalfa was measured on two 0.5 m² subsamples per plot harvested three times per year and adjusted to a moisture content of 15.0%.

Statistical Analyses

Descriptive statistics (mean, variance, CV, skewness ratio, and kurtosis ratio) were estimated for each soil covariate at each sampling depth. Shapiro–Wilk’s test was conducted to test for normality of the distribution of each variable. Nonnormally distributed variables were transformed for statistical analyses then back-transformed for reporting. Spatial variability of the soil data was determined from measures of nugget and structural variance obtained from semi-variograms using GS+ Geostatistics for the Environmental Sciences Version 7.0 (GS+, 2007). Model selection and data transformation were specific for each variable and were based on the values of residual variance and coefficient of determination (R^2) in the regression model. The nugget variance (C_0 ; random variance) and the sill ($C_0 + C$; total variance) were used to estimate the structural variance (C),

which is the variance accounted for by spatial dependence. The ratio of the structural variance to the sill $C/(C_0 + C)$ was used as an indicator of the degree of randomness in the data’s spatial variability. This ratio was used to define three classes of spatial dependence for soil covariates: (i) when the ratio is >0.75 , the measured variable was considered strongly spatially dependent; (ii) when the ratio was between 0.25 and 0.75, the soil variable was considered moderately spatially dependent; and (iii) when the ratio is <0.25 , or the slope of the semi-variogram was about 0.0, the variable was considered random or nonspatially correlated (pure nugget). Spatial analysis was used to characterize the experimental site, identify the extent to which soil covariates are spatially variable, and to quantify the impact of the spatial variation of single and aggregate soil covariates on total yield, temporal yield variance, and coefficient of variation.

Annual crop yields (2002–2005) per plot were used to calculate TY, TYV, and CV for each plot. These yield statistics (i.e., dependent variables), used in final statistical analyses, were based on weighted mean yield data per plot using mechanically- and hand-harvested subsamples. A temporal yield variance was estimated (Whelan and McBratney, 2000) for plot i as

$$\sigma^2_{Ti} = \sum (Y_{ij} - Y_i)^2 / n - 1$$

where Y_{ij} is the yield value of plot i ($i = 1-192$) in year j ($j = 1-4$) and Y_i is mean yield value of plot i for all years, and n is number of years. Analysis of variance for a split plot in a randomized complete block design was conducted on the TY, TYV, and CV data for the whole experiment, with cropping

systems (CNV and ORG) in whole-plots and the combined RTF management factors in subplots.

A linear mixed model, using Residual Maximum Likelihood (REML; Payne et al., 2007), of the form $Y_{ijk} = \mu + \Sigma(x_{ik} - \bar{x}_{..}) + b_i + \tau_j + d_{ij} + \gamma_k + (\tau\gamma)_{jk} + e_{ijk}$ was used to perform the statistical analyses for the whole experiment; where Y_{ijk} is rotation yield associated with i th block, j th system, and k th RTF treatment combination, μ is an overall mean; $(x_{ik} - \bar{x}_{..})$ is the effect of a covariate (x_{ik} is a covariate in the i th block and k th subplot and $\bar{x}_{..}$ is its mean); b_i is $\sim N(0, \sigma^2_B)$ is the random effect of block i ; τ_j is the fixed main effect of treatment (system) j ; $d_{ij} \sim N(0, \sigma^2_p)$ is the random plot error for the experimental unit in block i receiving treatment (i.e., system) j ; γ_k is the fixed main effect of the RTF treatment combination k ; $(\tau\gamma)_{jk}$ is the fixed interaction effect that is associated with system j and RTF k ; and $e_{ijk} \sim N(0, \sigma^2)$ is the random error that is associated with the yield measurement in plot k on the experimental unit in block i receiving treatment j . The cumulative effect of covariates at the blocks level and at the whole-plot levels were tested against d_{ij} and e_{ijk} , respectively.

Due to the unique experimental design where three (rather than one) factors were assigned to the subplots, data for the CNV and ORG systems were analyzed separately using an unbalanced ANOVA with one error term to test the significance of main and interaction effects of R, T, and F (Payne et al., 2007). A model of the form

$Y_{ijkl} = \mu + (x_{ik} - \bar{x}_{..}) + b_i + \tau_j + a_k + \gamma_l + (\tau a)_{jk} + (\tau\gamma)_{jl} + (a\gamma)_k + (\tau a\gamma)_{jkl} + e_{ijkl}$ was used to perform the analyses for each cropping system separately, where Y_{ijkl} is the yield measurement, Y_{ijk} is the yield associated with i th block, j th rotation (R), k th tillage (T), and l th F treatment combination, μ is an overall mean; $(x_{ik} - \bar{x}_{..})$ is the effect of a covariate (x_{ik} is a covariate in the i th block and k th subplot and $\bar{x}_{..}$ is its mean); b_i is $\sim N(0, \sigma^2_B)$ is the random effect of block i ; τ_j is the effect of the j th rotation, a_k is the effect of the k th tillage, γ_l is the effect of the l th fertility treatment, and $e_{ijkl} \sim N(0, \sigma^2)$ is the random error that is associated with the yield measurement in plot k on the experimental unit in block i receiving treatments j , k , and l . Single, two-way, and three-way interactions of R, T, and F, and covariate effects were tested against e_{ijkl} . All three-way interactions were not significant and are not reported.

Calibration partial least square regression models were developed to predict TY for each cropping system and crop rotation as a function of all management subfactors and soil covariates. A model of the form: $\mathbf{X} = \mathbf{t}_1\mathbf{p}'_1 + \mathbf{t}_2\mathbf{p}'_2 + \dots + \mathbf{t}_M\mathbf{p}'_M + \mathbf{E}_M$, was used in PLS regression, where \mathbf{X} is a matrix of explanatory variables given by the vector \mathbf{y} (see below), \mathbf{p}'_M are K -dimensional vectors called \mathbf{X} -loadings, \mathbf{E}_M is the residual matrix, and $\mathbf{y} = \mathbf{t}_1q_1 + \mathbf{t}_2q_2 + \dots + \mathbf{t}_Mq_M$, where \mathbf{t}_M (M are the latent variables) and the q_M are the \mathbf{y} -loadings. In this model, the dependency among the K -explanatory variables is broken up, and the relationship between \mathbf{X} and \mathbf{y} is transmitted through the latent variables \mathbf{t}_M . The calibration PLS models were cross-validated by successively leaving out one data point at a time, a model was built using the remaining data points, then the new model was used to predict the dependent variable (Geladi and Kowaliski, 1986; Wallach and Goffinet, 1987). Finally, deviations (\pm SE) from mean TY, TYV, and CV were calculated for each RTF combination and rotation-phase combinations to contrast and select best combinations of management practices within each cropping system. Temporal yield variance $[(\text{Mg ha}^{-1})^2]$ was used

as a measure of the consistency of yield patterns associated with single or multiple factors in the experiment (Florin et al., 2009), and the CV was used as an initial measure of data heterogeneity and of relative precision (Blackmore et al., 2003). The root mean square error (RMSE, Mg ha^{-1}) was used to evaluate the PLS model performance based on the agreement between predicted and observed yield values (Wallach and Goffinet, 1987) and was calculated as $[\Sigma(y_m - y_p)^2/n]^{0.5}$, where y_m and y_p are measured and predicted rotation yield, respectively, and n is number of observations. Relevant modules in GenStat Version 10 (Payne et al., 2007), and STATISTICA Release 9.1 (StatSoft, 2010) were used in data processing, statistical analyses, and modeling.

RESULTS

Spatial Variation and Site Characterization

Descriptive statistics, tests of significance, percent structural variance and spatial classes based on GIS models for soil covariates are presented in Table 1. The five soil series (Barnes, Flom, Hamerly, Parnell, and Vallers) identified in the experimental site have a relatively uniform soil texture within the surface 30 cm (Soil Survey Staff, 2004). The carbon-related covariates, except C/N, were highly variable, followed by ECa-V and ECa-H; whereas, BD and pH estimates were among the least variable. Positive (e.g., ECa-H, ECa-V, IC, and SC) and negative skewness ratios (e.g., clay and pH) as well as positive (e.g., BD, clay, pH) and negative kurtosis ratios (e.g., sand and silt) characterized most soil covariates. Spherical GIS models fitted 50% of all soil covariates, with structural variances ranging from 0.43 to 0.96 and a strong spatial dependence; the remaining soil covariates fitted Linear, Exponential or Gaussian models with moderate to strong spatial dependences. The two major soil series, Barnes loam and Hamerly clay loam, covered 44.3 and 42.7%, respectively, of total land area in the experimental plots; the remaining minor soil series, Flom, Parnell and Vallers, covered 3.6, 4.2, and 5.2%, respectively. Mean separation, by Tukey's HSD test, indicated significant differences among two or three groups of soil series for all soil covariates (Table 2). Discriminant analysis, using all soil covariates, correctly classified the soil series with varying levels of accuracy. Flom was 100% correctly classified; whereas Barnes (98.7%), Hamerly (96.8%), Vallers (85.7%), and Parnell (76.0%) were correctly classified with decreasing level of accuracy.

Sources of Yield Variation

Results of statistical analyses using a mixed model appropriate for a split-plot ANOVA are presented in Table 3. As a group, soil covariates at the blocks, and subplots levels had no significant effect on TY, TYV, or CV estimates, except for the negative impact on TYV ($p = 0.10$) and CV ($p = 0.009$) at the blocks level. Nevertheless, when included in the statistical analyses, covariates influenced variance estimates and impacted the level of significance of SYS and RTF but not their interaction (Table 3). When soil covariates were included in the statistical analyses, the LSD estimates for the SYS, but not for RTF or their interaction, were twice as large as those when covariates were not included. Therefore, the former was used for means comparisons to achieve more rigorous separation between treatment means. The SYS factor accounted for the greatest portion of variances in TY, TYV, and CV, followed in decreasing order, by RTF and $\text{SYS} \times \text{RTF}$, whether soil covariates were

Table 2. Mean separation and percent correct classification based on soil covariates of five soil series in a cropping systems field experiment.

Soil attribute/variable	Soil series				
	Barnes	Flom	Hamerly	Parnell	Vallers
Sand, %	35.8a†	33.9b	36.5a	35.3a	36.6a
Silt, %	36.3b	39.6a	36.9b	39.5a	35.0b
Clay, %	27.9a	26.5b	26.8b	25.2c	28.0a
Bulk density (BD)	1.15b	1.19b	1.19b	1.2a	1.2a
pH	7.76b	7.91a	7.71b	7.93a	7.73b
Electrical conductivity					
ECaH, dS m ⁻¹ ‡	26.86d	34.67ab	30.55c	33.57b	36.77a
ECaV, dS m ⁻¹	30.22c	38.22a	34.76b	37.54ab	41.12a
Carbon					
Inorganic, IC, %	0.316c	0.605a	0.322c	0.634a	0.407b
Soluble, SC [mg kg ⁻¹ (×1000)]	0.069c	0.088ab	0.077b	0.076bc	0.098a
Microbial Biomass, MBC, [mg kg ⁻¹ (×1000)]	0.998ab	0.837c	0.949b	0.979ab	1.051a
C/N	13.74b	14.81ab	13.72b	15.08a	13.79b
Correct classification, %	98.7	100.0	96.8	76.0	85.7

† Means within rows followed by the same letter do not differ significantly (Tukey HSD, $p < 0.05$).

‡ ECaH, horizontal apparent electrical conductivity; ECaV, vertical apparent electrical conductivity; SC, soluble carbon; MBC, microbial biomass carbon.

included in the analyses or not. Variance in TY, TYV, and CV due to SYS was reduced by 52, 44, and 51%, respectively, and remained significant after correcting for soil covariates. No such changes were found for RTF or SYS × RTF.

Comparisons between Cropping Systems

Results of an unbalanced ANOVA for each cropping system, with and without soil covariates, are presented in Table 4. The adjusted R^2 values for TY, TYV, and CV in each cropping system were larger when soil covariates were included in the analyses. The magnitude of adjusted R^2 values depended on the cropping system and on the dependent variable in question and ranged from

a maximum of 0.62 for TY in CNV when soil covariates were included to a minimum of 0.07 for CV when soil covariates were not included in the analysis. Soil covariates differed as to their impact on each of the three dependent variables in both cropping systems. The BD, clay, and silt had no significant effects on all three dependent variables in ORG; similarly, SC, MBC, C/N, pH, ECaH, and silt had no significant effects on all three dependent variables in CNV. The BD and clay content had significant effects on all three dependent variables in CNV; whereas IC had significant effects on all three variables in both cropping systems. The ECaV had significant effects on TYV and CV in both cropping systems; C had significant effects on TYV and CV in ORG; C/N

Table 3. Analyses of variance for total rotation yield (TY). Temporal yield variance (TYV) and coefficient of variation (CV) and variance components due to factors and covariates in a cropping systems field experiment.

Variable	Factor	Covariates Coefficient (± SE)	With covariates			Without covariates		
			MS†	p	LSD	MS	p	LSD
TY	Blocks					12.5	0.950	
	Covariates	−0.098 (0.08)	15.7	0.35				
	System		931.4	0.03	5.0	1951.0	0.002	2.1
	Covariates	−0.03 (0.15)	1.2	0.85				
	Rotation × Tillage × Fertility (RTF)		28.3	0.003	3.5	27.7	0.003	3.5
	SYS × RTF		10.9	0.65	5.2	11.3	0.620	5.1
TYV	Covariates	0.034 (0.023)	18.5	0.23				
	Blocks					18.2	0.960	
	Covariates	−0.159 (0.06)	41.4	0.13				
	SYS		480.7	0.12	7.8	852.0	0.020	3.2
	Covariates	−0.04 (0.24)	2.5	0.86				
	RTF		60.7	0.003	5.2	62.4	0.002	5.2
CV	SYS × RTF		24.4	0.62	7.8	24.3	0.630	7.5
	Covariates	0.014 (0.042)	2.9	0.74				
	Blocks					29.6	0.890	
	Covariates	−0.23 (0.02)	87.1	0.009				
	SYS		2269.0	0.03	7.1	5582.0	0.001	3.0
	Covariates	−0.1 (0.22)	12.2	0.70				
	RTF		508.1	0.03	17.7	533.0	0.020	17.0
	SYS × RTF		392.1	0.16	24.0	419.0	0.110	23.6
	Covariates	−0.14 (0.14)	288.0	0.33				

† MS, means of squares.

Table 4. Analyses of variance (unbalanced ANOVA) for total rotation yield (TY) temporal yield variance (TYV) and CV and variance components due to factors and covariates in a conventional and organic cropping systems field experiment.

Var	Factor/ Covariate	Conventional system		Organic system	
		<i>p</i> (with covariates)	<i>p</i> (without covariates)	<i>p</i> (with covariates)	<i>p</i> (without covariates)
TY	BD†	0.001		0.460	
	SC	0.890		0.910	
	IC	0.003		0.070	
	MBC	0.380		0.130	
	C/N	0.240		0.020	
	pH	0.300		0.005	
	ECaH	0.430		0.004	
	ECaV	0.270		0.004	
	Clay	0.020		0.850	
	Silt	0.080		0.320	
	Rotation (R)	0.620	0.760	0.290	0.460
	Tillage (T)	0.070	0.030	0.770	0.890
	Fertility (F)	0.001	0.001	0.090	0.310
	R × T	0.001	0.001	0.050	0.130
	R × F	0.001	0.005	0.010	0.040
	T × F	0.550	0.310	0.090	0.470
	R ²	0.620	0.570	0.500	0.310
TYV	BD	0.002		0.560	
	SC	0.310		0.020	
	IC	0.003		0.001	
	MBC	0.750		0.910	
	C/N	0.710		0.020	
	pH	0.370		0.940	
	ECaH	0.120		0.280	
	ECaV	0.020		0.780	
	Clay	0.003		0.140	
	Silt	0.300		0.130	
	R	0.090	0.350	0.450	0.540
	T	0.540	0.680	0.050	0.040
	F	0.010	0.001	0.010	0.020
	R × T	0.008	0.020	0.460	0.270
	R × F	0.020	0.060	0.009	0.050
	T × F	0.860	0.690	0.400	0.220
	R ²	0.450	0.250	0.350	0.170
CV	BD	0.007		0.190	
	SC	0.170		0.020	
	IC	0.020		0.050	
	MBC	0.670		0.070	
	C/N	0.710		0.780	
	pH	0.330		0.070	
	ECaH	0.090		0.140	
	ECaV	0.020		0.030	
	Clay	0.001		0.830	
	Silt	0.210		0.740	
	R	0.010	0.070	0.370	0.620
	T	0.050	0.340	0.020	0.050
	F	0.870	0.420	0.510	0.340
	R × T	0.730	0.820	0.060	0.030
	R × F	0.380	0.180	0.770	0.850
	T × F	0.630	0.850	0.540	0.640
	R ²	0.330	0.070	0.300	0.160

† BD, bulk density; SC, soluble carbon; IC, inorganic carbon; MBC, microbial biomass carbon; ECaH, horizontal apparent electrical conductivity; ECaV, vertical apparent electrical conductivity.

Table 5. Mean and standard error of the mean (SE) of total rotation yield (TY; Mg ha⁻¹), temporal yield variance [TYV, (Mg ha⁻¹)²] and coefficient of variation (CV, %), and significant ($p < 0.05$) deviations above (+), below (-), or on-the-mean (0; $p > 0.05$) for different phases of a combination of crop rotation-tillage-fertility treatments in a conventional and organic cropping system.

Crop rotation	Tillage-Fertility combination	Rotation phase	Conventional system			Organic system		
			TY	TYV	CV	TY	TYV	CV
Mean			21.9	12.3	61.1	15.4	7.8	72.0
SE			0.35	0.66	0.98	0.47	0.47	2.4
2-Yr	CT-NF†	CS	–	0	0	0	0	–
		SC	–	0	0	–	0	0
	CT-YF	CS	0	0	0	–	–	–
		SC	+	+	+	+	+	0
	ST-NF	CS	–	0	0	–	–	+
		SC	–	–	0	–	0	+
	ST-YF	CS	0	0	0	0	0	0
		SC	+	+	+	+	+	+
4-Yr	CT-NF	ACSW	0	+	+	+	–	–
		WACS	+	0	0	+	0	0
		SWAC	–	–	0	0	–	–
		CSWA	–	–	0	0	0	–
	CT-YF	ACSW	+	0	–	+	0	–
		WACS	+	+	0	0	+	+
		SWAC	+	+	0	–	–	–
		CSWA	0	–	–	+	0	–
	ST-NF	ACSW	–	–	–	–	–	–
		WACS	–	0	0	0	+	+
		SWAC	–	–	0	–	0	0
		CSWA	–	–	0	–	0	0
	ST-YF	ACSW	–	–	–	–	0	–
		WACS	0	0	0	0	+	+
		SWAC	0	–	+	–	0	–
		CSWA	+	0	0	+	0	–

† CT, conventional tillage; NF, nonfertilized; YF, fertilized; C, corn; S, soybean; A, alfalfa; W, wheat.

had significant effects on TY and TYV in the ORG; MBC and pH had significant effects on CV in the ORG; and finally, ECaH had a significant effect on TY in ORG.

The single and multiple diverse effects of soil covariates on one or more dependent variables influenced the impact of subplot management factors (R, T, and F) and their interactions on these variables. The rotation had the smallest number of significant effects on the dependent variables, followed by tillage or fertility factors. The tillage factor had significant effects only on TY in the CNV and on TYV and CV in ORG, in addition to its significant effect on CV in the CNV when soil covariates were included in the analyses; whereas the fertility factor had significant effects on TY and TYV, but not on CV, in the CNV; whereas, it failed to impact TY and CV in ORG. The two-way interaction effects differed as to their level of significance and the number of dependent variables they impacted. The R×T and R×F had more significant effects than T×F on most variables in both cropping systems whether covariates were included in the analyses or not. The T×F had no significant effects on TY and TYV, and all three two-way interactions had no significant effects on CV in either cropping system regardless of covariate effects, except the significant effect of R×T on CV in ORG. None of the three-way interactions were statistically significant and are not reported.

Yield and Variance Instability

Means and standard errors of TY and its TYV and CV in CNV and ORG systems are presented in Table 5; the cropping

systems differed significantly ($p = 0.001$) in mean TY, TYV, and CV. Overall means (adjusted for soil covariates and averaged over all rotation-tillage-fertilizer combinations within each cropping system) of TY, TYV, and CV for CNV [21.9 Mg ha⁻¹, 12.4 (Mg ha⁻¹)², and 61.1%, respectively]; are contrasted with those of ORG system [15.4 Mg ha⁻¹, 7.8 (Mg ha⁻¹)², and 72.0%, respectively]. Large and significant differences between rotation phases for TY, TYV, and CV among and within cropping systems are demonstrated by the deviations of these variables from their respective means. The classification based on whether a value is significantly above (+), below (-), or does not significantly differ (0) from its respective mean, produced a large number of TY–TYV–CV combinations reflecting the complex nature of relationships between these response variables.

The soybean–corn phase of the traditional 2Yr crop rotations, in combination with conventional or strip tillage (CT and ST, respectively) and fertilizer (YF) in CNV and ORG (Table 5) produced larger TY and resulted in larger TYV (i.e., less consistency of yield pattern) than their respective overall means; however, the ST–YF management combination in ORG was less stable (as measured by CV) than in CNV. Additionally; strip tillage resulted in significantly larger CV than the mean in the ORG regardless of rotation phase. The remaining RTFs resulted in different combinations of significantly above-, below-, or on-the-mean values for TY, TYV, and CV. The WACS and SWAC phases of the 4-Yr crop rotation and conventional tillage with fertilizer (CY) management practice in CNV produced significantly

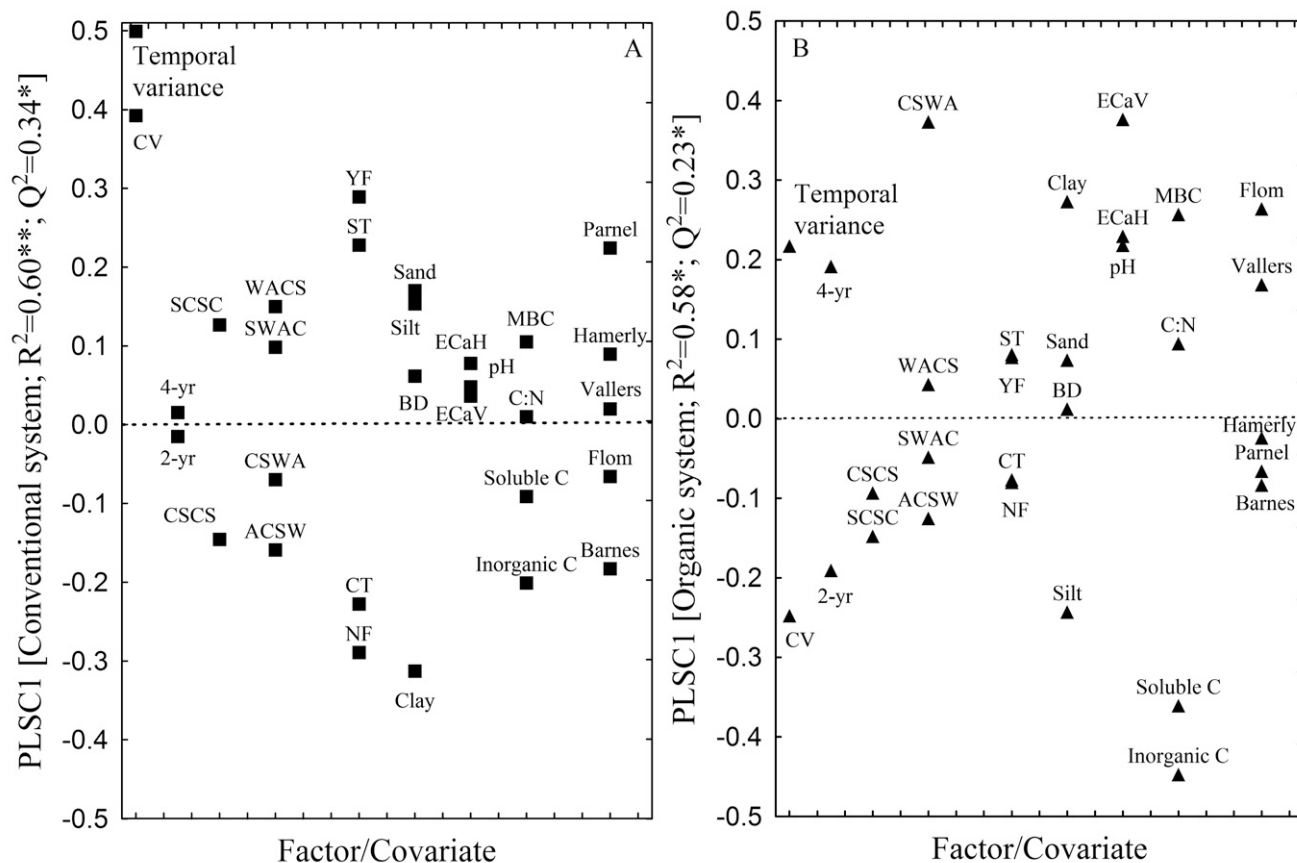


Fig. 1. Coefficients of the first partial least squares (calibration [R^2] and validation [Q^2]) regression component predicting total rotation yield as a function of all factors and covariates in (A) Conventional and (B) Organic cropping systems.

larger TY, which was characterized by larger TYV and relatively stable (i.e., does not significantly differ from the mean) CV, as compared with their respective overall means. On the other hand, ACSW and WACS phases of the 4-Yr crop rotation and conventional tillage with no fertilizer management practice in ORG produced significantly larger TY and stable or below average TYV and CV as compared to their respective means.

Modeling Total Rotation Yield

The first Partial Least Squares Component (PLSC1) predicting TY as a function of management subfactors, soil covariates, TYV, and CV for each cropping system (Fig. 1) and crop rotation (Fig. 2) accounted for different amounts of variation as indicated by the calibration (R^2) and validation (Q^2) model coefficients of determination and by loadings (i.e., correlation coefficients between each factor or soil covariate and PLSC1) of factors and covariates on PLSC1. Calibration and validation models had better fit for TY of the 2-Yr crop rotation (79 and 52%, respectively) and the 4-Yr (65 and 44%, respectively) crop rotations as compared to TY of CNV (60 and 34%, respectively) and ORG systems (58 and 23%, respectively). Larger differences were found between loadings of factors, covariates, TYV, and CV on PLSC1 of both cropping systems as compared to differences between 2-Yr and 4-Yr crop rotations. A major difference between the cropping systems is that TYV and CV were positively correlated with PLSC1 (Fig. 1) and had greater impact on TY in CNV; whereas, TYV had a positive, albeit smaller loading on PLSC1, and therefore, had smaller impact on TY in ORG. Crop rotations, but not their phases, did not differ in their impact on

TY of CNV; whereas, for example both crop rotations and the CSWA crop phase displayed larger impacts on TY of ORG. Both cropping systems contributed the most to yield variation within crop rotations as quantified by their loadings on PLSC1 (Fig. 2). However, smaller differences were found in loadings of management subfactors and soil covariates between 2-Yr and 4-Yr crop rotations except for a larger impact of the fertility factor on TY of the 2-Yr as opposed to a larger impact of the tillage factor on TY of the 4-Yr crop rotation. The impact of the soil covariates, including clay, silt and sand content, whether comparing cropping systems or crop rotations, is mediated by the occurrence of major (Barnes and Hamerly) and minor (Flom, Parnell, and Vallery) soil series subjected to these management factors. The two major soil series constituted 75 and 93.8% of the land area under CNV and ORG systems, respectively; whereas, they constituted 89 and 82% of the land area under 2-Yr and 4-Yr crop rotations, respectively.

Total Yield as a Function of Temporal Yield Variance or Coefficient of Variation

Large and significant differences were found between TY estimates due to most levels of factors included in the analyses, except crop rotations when averaged over cropping systems (Table 6). The largest TY in CNV (24.3 Mg ha^{-1}) was produced by both 2-Yr and 4-Yr crop rotations using conventional tillage with fertilizer; whereas, the largest TY in ORG (18.6 Mg ha^{-1} , which was 76.5% of TY in CNV) was produced by the 4-Yr under conventional tillage, with or without fertilizer. On the other hand, the smallest TY's in CNV and ORG systems were 20 and 30% less than their respective largest yields. Applying

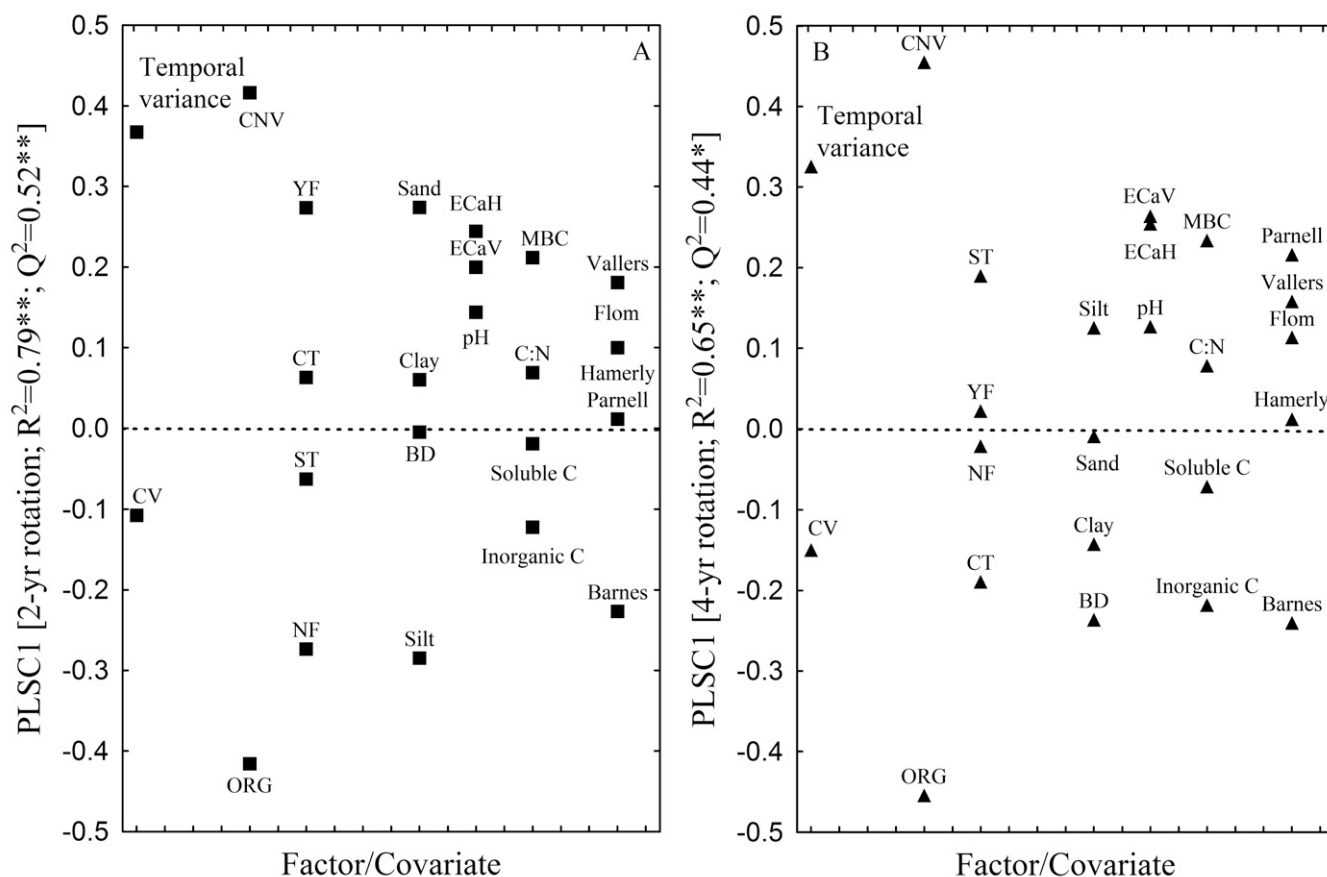


Fig. 2. Coefficients of the first partial least squares (calibration [R^2] and validation [Q^2]) regression component predicting total rotation yield as a function of all factors and covariates in (A) 2-yr and (B) 4-yr crop rotations.

the recommended fertilizer rates, whether using conventional or strip tillage, resulted in larger absolute or relative RMSE values as compared with the no-fertilizer treatment (NF), especially in ORG. However, the fertilizer advantage was relatively large (19%) in CNV, regardless of crop rotation or tillage; whereas, in ORG, it became small when conventional tillage was used with 2-Yr and 4-Yr crop rotations, (5 and 10%, respectively), and large when strip tillage was used with 2-Yr and 4-Yr crop rotation, (18 and 21%, respectively). Coefficients of the PLS regression models predicting TY as a function of TYV or CV in both cropping systems (i.e., regression coefficient [β], RMSE, and the coefficient of determination for the validation PLS regression model [Q^2]) pointed to major differences between and within cropping systems. Temporal variance was more instrumental in predicting TY than was the CV, had more significant regression coefficients (β 's) relating TY to TYV in CNV than in ORG, and resulted in smaller RMSE values, and consequently larger fit (i.e., Q^2) in CNV as compared with ORG.

DISCUSSION

Spatial and Temporal Variation

The underlying hypothesis, when designing field experiments, is that spatial variation is random. Consequently, proper interpretation of experimental data largely depends on the "best" estimation of experimental error, which is most likely achieved by analysis of temporal stability of spatially-dependent factors affecting yield (Cassel et al., 2000). Therefore, there is a serious need to further research how TYV impacts farmers' ability to

manage spatial variation, knowing that the former has a cyclical nature and is usually larger than the latter (Blackmore et al., 2003). Trends in soil covariates in the current and other studies (e.g., Machado et al., 2002) did not fully explain variation in observed rotation yields and their temporal variances; whereas temporal effects, also reported by Machado et al. (2002), did explain more than 50% of yield variation, and up to 86% of total rotation yield variation in this study. The complex inter-relationships among soil covariates are largely responsible for crop productivity; some of these covariates (e.g., C content) are likely to change with management, others (e.g., ECaH, ECaV, and MBC) with time (Cerri et al., 2004), but all are likely to affect crop response variables (Cassel et al., 2000; Pringle et al., 2004). Although soil covariates were not monitored during all 4 yr of this phase of the experiment, they impacted to varying degrees total rotation yield and its temporal yield variance and coefficient of variation. Previous research on temporal variation in cropping systems has focused on estimating regional yield averages using temporal fractal (Eghball and Power, 1995) or geostatistical analyses (Florin et al., 2009). Nevertheless, the understanding of spatiotemporal variation gained in the current and a few other studies (e.g., Bakhsh et al., 2000; Varvel, 2000; Grover et al., 2009) can help improve site-specific and long-term management (Grover et al., 2009).

Sources of Yield Variation

Cropping systems research offers the opportunity to integrate covariance structures for temporal variation with those of spatial

Table 6. Mean separation of measured total rotation yield (TY) and partial least squares validation models predicting TY as a function of TYV or CV in conventional and organic cropping systems, crop rotations, and combinations of cropping systems–rotations–tillage–fertility treatments.

Factor(s)				Measured yield	Independent variable					
System	Rotation	Tillage	Fertility		Temporal variance			Coefficient of variation		
					β †	RMSE	Q^2	β	RMSE	Q^2
				Mg ha ⁻¹						
All				18.6	0.58	3.55	0.50	−0.08	4.79	0.07
CNV‡				21.9a§	0.58	3.54	0.49	0.18	3.13	0.22
ORG				15.4b	0.44	3.67	0.22	−0.07	3.89	0.12
	2-Yr			18.4a	0.62	2.98	0.62	−0.08	4.75	0.02
	4-Yr			18.7a	0.57	3.80	0.44	−0.08	4.86	0.08
CNV	2-Yr	CT	NF	20.4b	0.51	1.70	0.85	0.32	4.32	0.07
			YF	24.3a	0.36	1.71	0.51	0.15	2.45	0.00
		ST	NF	19.5b	0.49	1.69	0.86	0.30	4.36	0.07
			YF	23.2a	0.41	1.64	0.66	0.24	2.61	0.14
	4-Yr	CT	NF	20.6b	0.43	1.79	0.67	0.13	2.83	0.22
			YF	24.3a	0.40	1.47	0.70	0.21	2.28	0.30
		ST	NF	19.5b	0.55	1.66	0.74	0.21	2.85	0.20
			YF	23.1a	0.34	1.68	0.66	0.12	2.55	0.23
ORG	2-Yr	CT	NF	14.9a	0.64	2.58	0.17	0.01	3.68	0.00
			YF	15.7a	0.53	4.28	0.05	−0.07	4.80	0.00
		ST	NF	13.6b	0.53	2.70	0.35	−0.06	3.92	0.00
			YF	16.0a	0.26	3.20	0.00	−0.04	3.34	0.00
	4-Yr	CT	NF	16.9a	0.48	2.56	0.17	−0.07	2.89	0.00
			YF	18.6a	0.61	4.83	0.10	−0.10	5.85	0.00
		ST	NF	13.0c	0.39	3.41	0.29	−0.14	4.22	0.00
			YF	15.7b	0.45	4.84	0.24	−0.08	5.11	0.18

† Partial Least Squares Regression Coefficients in bold are significant; $p < 0.05$.

‡ CNV, conventional cropping system; ORG, organic cropping system; CT, conventional tillage; ST, strip-tillage; NF, nonfertilized; YF, fertilized.

§ Means within each category (i.e., systems, rotations, or system–rotation–tillage–fertility combination), followed by the same letter do not differ significantly, Tukey HSD, $p < 0.05$.

variation (Singh and Jones, 2002). We used TYV as a measure of consistency of yield patterns (Florin et al., 2009), and CV as an initial measure of data heterogeneity and yield stability (Blackmore et al., 2003; Rozenzweig and Tubiello, 2007). Meyer-Aurich et al. (2006) reported that yield variances of individual crops in corn-based cropping systems were not affected by crop rotation or tillage factors. However, in the current study, all three response variables (i.e., TY, TYV, and CV) were affected by the $R \times T \times F$ interaction across cropping systems (Table 3). The effects of individual or two-way interactions between these management factors were dependent on the cropping system and on soil covariates (Table 4). The largest variation found in this study was due to cropping systems; whereas, variations attributed to interaction components were the smallest (Table 3). In addition, the variance due to covariates in all three dependent variables was the least at the subplots level, presumably due to differences between soil types. Differences in soil types were singled out, in addition to crop rotations, as major contributors to yield variability in ORG systems (Olesen et al., 2002). The impact of soil types in this study, as quantified by the incremental amount of variation (R^2) attributed to covariates (Table 4), were much larger for TY in ORG (0.19) as compared to CNV (0.05), almost equal for TYV (0.20 and 0.18, respectively), and almost twice as large for CV in CNV (0.26) as compared to ORG (0.14). Although variation can be managed to some degree through investment and knowledge, there will be some inherent uncertainty in the expected response to these inputs (Varvel, 2000; Rozenzweig and Tubiello, 2007).

Comparisons of Total Rotation Yield and Temporal Yield Variance between Cropping Systems

Most of the scientific literature before 2000 suggested that ORG systems were less productive than the CNV, higher-input systems. Total yield under ORG in this study approached 80% of that obtained under CNV after 4 yr of applying the respective management practices. Posner et al. (2008) reported a smaller gap (10%) when corn and soybean were produced under ORG for longer periods. Reduced yields under ORG have been attributed to weed competition and lack of available N; however, under drought conditions, crop yields of ORG have exceeded those of CNV (Pimentel et al., 2005; Miller et al., 2008). Nonetheless, the long-term viability of ORG in this ongoing experiment will be adequately assessed in the future by statistical analyses and modeling of additional crop yields and soils data.

In addition to the environmental cost often associated with CNV systems, crop yields in these systems may be more prone to temporal variability as suggested by Smith and Gross (2006) and confirmed by this study. This is in contrast to ORG systems, in which total yields were significantly less variable (Table 5), and some approached those produced by CNV systems (Table 6). Schmer et al. (2010) used temporal variance to identify relationships to yield within and across switchgrass cropping systems in the Northern Great Plains and suggested that analysis of temporal yield variation within a field would be useful for management purposes. In the present study, temporal variance was used to identify management combinations

that have large TY and large TYV, small TY and small TYV, or combination of both (Table 5). The relationship between TY and TYV differed between as well as within cropping systems; it was positive across all management scenarios, weaker in ORG as compared to CNV, and not always significant.

Although many $R \times T \times F$ management combinations under both CNV and ORG systems produced lower than average yields, the ORG had lower TYV and more management combinations with lower than average CV's implying that traditional chemical management practices are not necessary for maintaining stable yields. The "buffering capacity" of organic inputs, which is expected to improve nutrient and water availability over time (Pimentel et al., 2005), is likely to impart yield stability in ORG systems (Pimentel et al., 2005; Smith et al., 2007). Although yields were at or above average with conventional than with strip tillage for both cropping systems, management combinations with strip tillage had lower TYV under CNV, but conventional tillage had lower TYV and CV under ORG. Govaerts et al. (2007) documented greater yield stability in cropping systems with conventional tillage or in zero-till systems with residue retention as opposed to zero-till systems with residue removal. Our findings, along with those reported by Govaerts et al. (2007), tend to emphasize the potential positive role of organic matter (under strip tillage) and mechanical weed control (under conventional tillage) on total rotation yield of ORG systems. Nevertheless, more detailed and long-term studies will be necessary to fully understand how specific organic management practices affect crop yields and their stability (Smith et al., 2007).

Regardless of the strength of the relationships described above, TYV and CV can be used as a measure of stability in crop production and, when applied on a cropping system or field scale, provide guidelines to develop improved management practices (Whelan and McBratney, 2000; Smith and Gross, 2006). To this effect, we developed a classification scheme (Table 5) based on the level of variation around the mean of TY, TYV, and CV for each cropping system which also represents production risk (Blackmore et al., 2003), which is one of the factors that influence farmers' decisions to adopt a new management practice or production strategy. Furthermore, production risk raises the question of whether to manage spatial variation in the presence of temporal variation at a large field scale (Whelan and McBratney, 2000). Nevertheless, reducing yield variability can be accomplished through proper management at a field scale (Varvel, 2000). Notwithstanding the role of long-term experiments to help determine the sustainability of cropping systems (Berzsenyi et al., 2000), they can be used as an "early warning system" to identify threats to future productivity. In the first phase of this study, we demonstrated that sustainability indicators such as TY, TYV, and CV derived from comparisons of cropping systems and evaluated by means of a classification scheme provide an effective method for identifying combinations of management practices which are likely to be more stable and potentially sustainable.

Temporal variation in crop yields has considerable impact at farm, regional, and national levels (Porter et al., 2003; Posner et al., 2008), and a better understanding of the factors contributing to this variation, especially in row crops, is needed. Diverse rotations are expected to produce larger yields and to have smaller temporal variances than simple rotations or monoculture (Grover et al., 2009). This expectation was not always supported by the present

study, especially when using different levels of tillage and fertility in contrasting cropping systems. Under comparable experimental conditions, conventional rotations produced largest crop yields, followed, in decreasing order, by conventional monoculture and organic rotations (Smith and Gross, 2006). Although there were no indications that the overall total rotation yields differed significantly, some rotation-management combinations were less stable than others depending on the cropping system (Table 5). Where there was a lack of temporal stability, regardless of its positive or negative relation to TY (Table 5), greater influence or interaction of soil covariates with biotic and abiotic stresses, and management practices might have occurred (Bakhsh et al., 2000).

Modeling Total Yield

The PLS regression is particularly useful in obtaining more parsimonious models for predicting yield variation (Vargas et al., 2001). The results of PLS analyses (Fig. 1 and Fig. 2) provided a basis to visualize the interaction of management practices with other factors and covariates. The interactions of crop rotations with soil covariates (e.g., ECa-H, ECa-V, pH, C, and CI; Fig. 1) demonstrated how differences in covariate loadings between cropping systems contributed to differences in TY and TYV. A similar situation can be visualized of the interactions between tillage and fertility, as indicated by their different loadings in different crop rotations (Fig. 2). These results could be used to strategically deploy appropriate management practices for a given cropping system or crop rotation (Vargas et al., 2001). For example, fields with high temporal variances and low spatial variances would indicate a uniform field where management practices could be prescribed for the entire field (Blackmore et al., 2003).

Total Rotation Yield as a Function of Temporal Yield Variance and Coefficient of Variation

An estimate of TYV provided a powerful indicator of the influence of multiple factors on crop yield as reported by Schmer et al. (2010), and when used to predict TY, it resulted in a much larger PLS model fit (Q^2) as compared to using an estimate of CV (Table 6) although all phases of each crop rotation were present each year. The larger Q^2 values were associated with smaller RMSE estimates; the latter ranged from 1.47 (CNV-4 Yr-CT-Y) to 4.84 (ORG-4yr-CT-YF) Mg ha⁻¹ and in relation to their respective TY values (24.3 and 18.6 Mg ha⁻¹), these were 6 and 26%, respectively. The RMSE values (Table 6) reflected differences between PLS model performances based on the agreement between predicted and observed yield values (Wallach and Goffinet, 1987). When TYV and CV were used in conjunction with other factors and soil covariates (Fig. 1 and 2), they loaded on opposite sides of PLSC1 except in CNV. Similarly, temporal variance had positive loadings (Fig. 1 and 2) and positive and mostly significant regression coefficients (Table 6) in predicting TY, indicating that large TYV values may result in larger but unstable TY as reported by Schmer et al. (2010). The most ideal situation is when TYV and CV reach optimum and minimum values, respectively, to obtain largest and most stable TY. Nevertheless, when faced with significant temporal variability, farmers may have difficulty in determining yield goals and planning field operations (Whelan and McBratney, 2000).

CONCLUSIONS

Spatial dependence in a relatively small (3.3 ha) land area of an experimental site selected for long-term cropping systems research has been statistically confirmed for physical, chemical, and biological properties of five soil series. Quantitative and qualitative measures were developed to identify and interpret possible causes of variation in TY, TYV, and CV of two contrasting crop rotations under CNV and ORG systems. We developed a classification scheme of cropping systems, crop rotation phases, and management practices based on the three-way relationships between TY, TYV, and CV, and deviations from their respective means. The scheme can be used to strategically deploy appropriate management practices for a given cropping system or crop rotation, and to obtain the largest and most stable yields. These findings are useful in formulating hypotheses on what specifically causes yield variation under certain soil conditions and management practices. Moreover, these findings will help researchers, crop consultants, and farmers optimize future on-farm research, thus maximizing their ability to detect true responses to management factors and forecast the ability of a production system to remain sustainable.

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